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Technological shape and size: A disaggregated perspective on sectoral innovation systems in renewable electrification pathways

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ABSTRACT

The sectoral innovation system perspective has been developed as an analytical framework to analyse and understand innovation dynamics within and across various sectors. Most of the research conducted on sectoral innovation systems has focused on an aggregate-level analysis of entire sectors. This paper argues that a disaggregated (sub-sectoral) focus is more suited to policy-oriented work on the development and diffusion of renewable energy, particularly in countries with rapidly developing energy systems and open technology choices. It focuses on size, distinguishing between small-scale (mini-grids) and large-scale (grid-connected) deployment paths in renewable energy. We explore how the development and diffusion of solar PV and wind technology evolve in these sub-sectoral systems. We find that innovation and diffusion dynamics differ more between small and large than between wind and solar. This has important analytical implications because the disaggregated perspective allows us to identify trajectories that cut across conventionally defined core technologies. This is important for ongoing discussions of electrification pathways in developing countries. We conclude the paper by distilling the implications of these findings in terms of the requirements and incentive mechanisms that shape different pathways.

1. Introduction

Kenya, like many other countries around the globe, is currently facing momentous energy decisions. With a low rural electrification rate and a large proportion of the population currently lacking access to electricity, increasing generating capacity and achieving 100% energy access is a key priority for the government. While the current electricity system relies mainly on hydropower, the expansion of renewable energy (RE) sources, especially wind and solar power, has been given a high priority in national policies such as the national development strategy Vision 2030 and the rural electrification master plan [1,2].

Within the context of a rapidly developing energy system, Kenya faces a number of important technological choices in terms not only of which technologies to prioritise, but also how to deploy them. The current policy frameworks have enabled a combination of government and private sector developments in the energy sector.

The concept of sectoral innovation systems (SIS) has been used to illuminate the factors affecting innovation dynamics within and across sectors. The SIS perspective is particularly concerned with highlighting sector-specific characteristics of industrial evolution [3]. From the sectoral perspective, increasing attention is paid to RE sectors and their development. In this paper, we argue that it is crucial to take a closer look at the RE sector and what constitutes such a sector in order to push further the disaggregation of trends in the sub-sectors of wind and solar PV. In examining differences in terms of size and shape across and between these sub-sectors, we raise questions regarding the definitions and boundaries of these renewable energy 'sectors'.

Thus the key research question of this paper is: *How do wind and solar markets in Kenya differ in terms of development and organisation, both across and within sectors*? We answer this question by mapping out current status and trends across the mini-grid and large-scale market segments for wind and solar PV technologies respectively. Then we use the SIS perspective to describe the characteristics of each sub-sector, their drivers and barriers, and discuss the similarities and differences between them. As detailed and up to date information on the development and dynamics of the solar and wind markets in Kenya were found to be lacking, this paper seeks to bring together preliminary insights from research conducted in 2015–2016.

The paper is structured as follows. Section 2 introduces the sectoral innovation systems approach and its three main dimensions, which are

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used as the analytical framework for the research. Section 3 briefly introduces the research methods. Section 4 presents the results in the form of a mapping of current status and trends across the mini-grid and large-scale market segments for wind and solar PV in Kenya. Section 5 then describes each of the four disaggregated sectoral innovation systems and their characteristics, drawing on the dynamics presented in Section 4. Section 6 discusses the similarities and differences across these sectors using the three main dimensions of the SIS approach as vectors. Finally, Section 7 pulls together the key findings of the research and provides a discussion of how the disaggregated SIS analysis can highlight the coexistence of different innovation systems within broadly defined sectors. It sums up by drawing insights for policy-makers and future research on shaping electrification pathways in countries where the process of electrification is ongoing. Our findings have wider significance because the size and shape of these pathways add-up as defining features of alternative electrification paradigms.

2. Disaggregating the innovation systems approach

Innovation systems approaches are increasingly used for the analysis of development problems, including development problems in Africa [4,5]. The sectoral systems perspective ascribes importance to learning, knowledge and capability accumulation in the innovation process [6]. The SIS perspective is based on the underlying assumption that innovation dynamics are closely related to the specific characteristics of a given sector or industry. Innovation within a sector is a dynamic process, which constantly transforms the structure and boundaries of a given industry. In this paper, the focus is on analysing two low carbon technologies, namely solar PV and wind technologies in Kenya.

While there are profound differences between low carbon technologies [7], the differences within solar PV and wind energy overarching technological categories are equally profound. To give an example, the notion of a 'solar technology' may be used as an umbrella term to describe solar-powered LED lamps, solar home systems and utility-scale solar power plants. Common to these systems is the fact that they make use of solar panels as the underlying source of electricity generation. However, it is clear that there are significant differences between the respective users, producers, investors, actors, prices, scales, R&D intensities, value chains, technical characteristics and competing technologies of these systems [5]. As noted by Stephan et al. [8], understanding such differences in sectoral configurations helps identify dynamics that otherwise go unnoticed. As a result, each of the subcategories of these systems of technology may more appropriately be considered units of analysis in their own right. In the delineation of specific sectors, a key question therefore concerns the selection of an appropriate level of aggregation in the analysis. Accordingly, the case of solar and wind technologies examined in this paper are understood as sub-sectors of the wider renewable energy sector, which in turn is considered a subset of the broader energy sector, and so forth. Initially, Malerba defined SISs broadly as "a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products" [9]. While this broad definition was developed with the intention to be able to cover research conducted at various level of aggregation, most empirical studies in this field focuses on a highly aggregated level of analysis covering the entire pharmaceutical, chemical, telecommunications or biotechnology sectors [6]. In this paper, we adopt a more disaggregated level of analysis in order to uncover in further detail the innovation dynamics within such overarching and broadly defined sectors.

Based on this understanding of technology, this paper distinguishes between small-scale mini-grids and large-scale power plants using solar and wind technologies to generate electricity. Mini-grids are understood as decentralised (off-grid) systems consisting of power-generating assets and distribution with power capacities of between 0.2 kW and 2 MW connecting two or more individual households [10]. Large-scale power plants are understood as grid-connected plants owned by utilities and/or private operators with installed capacities above 15 MW.

The above description translates into the conceptualisation of four different SISs in Kenya with distinctive sector-specific innovation features, which are explored in the paper: (i) wind-powered mini-grids; (ii) large-scale, grid-connected wind-power plants; (iii) solar-powered mini-grids; and (iv) large-scale, grid-connected solar power plants. Following the SIS perspective, three main dimensions are used to guide the analysis of these four sectors [3]:

- Knowledge and technologies
- Actors and networks
- Institutions

The knowledge and technology dimension focuses on the underlying knowledge bases of a given sector, which can be highly unique to the sector as a result of the interactions between the firms and organisations involved. The knowledge base in some sectors relies mainly on tacit know-how, craft and practical skills, while others depend more on codified knowledge and formal R&D [11,12]. This means that knowledge created within specific sectors may not be easily acquired and transferred across sectors.

The actors and networks within SIS may involve firms as well as non-firm actors and their mutual interaction in the dynamic learning and innovation processes within specific sectors. While firms play an important role, governments, universities, suppliers, financial institutions and NGOs are examples of other actors that take part in the innovation activities of a given sector [3].

The institutions of a given sector involve the surrounding infrastructure and enabling framework conditions in which innovation takes place. Such institutions can be more or less formal, ranging from laws, regulations and standards as formal, tangible institutions to norms, habits and routines as informal institutions resulting from repeated interactions among actors. These institutional conditions shape the involvement and interactions of actors and influence the learning processes that lead to the accumulation of knowledge and capabilities [6].

Using the SIS approach as an analytical framework also prompts bigger questions as to its strengths and drawbacks. As noted by Kern [13], one criticism of the innovation systems approach is the apolitical nature of its analyses, and while some aspects of politics may be covered by, for example, the institutional dimension of the framework used in this paper, others view the politics as pervasive across all the dimensions and functions of innovation systems. Although an explicit analysis of the agents of change that may reveal the relative differences and similarities of the four sectors is not included, the framework does explore the drivers and barriers for each sector. Revealing the differences and similarities of the dynamics across sectors makes possible a discussion of how policy-makers and stakeholders can take more informed decisions regarding how to nurture renewable energies across complementary sub-sectors. It is important to note here that the under- or over-prioritisation of certain sectors in relation to others is not simply based on technical decisions, but essentially involves political choices and prioritizations. Large-scale solar and wind-energy projects are essentially large infrastructure projects that are typically highly political in nature and that involve a multitude of actors with competing interests and negotiations across various levels. For example, some argue that the push for RE in Kenya is not necessarily being driven by environmental concerns, but rather by the need to provide access to electricity to the highest number of people within the shortest time possible [14]. These authors highlight the tensions that come from pursuing the multiple objectives of 'growth', 'inclusiveness' and 'sustainability' [15]. Few studies have addressed the political economies of the RE sector in Kenya with the exception of Newell and Phillips, who look at transitions in the energy sector more broadly [16].[1] By unpacking the innovation

[1] See also Ahlborg [55].

dynamics at a more disaggregated level, this study makes possible future research to facilitate a focus on the political reasons for the relative differences, strengths and weaknesses of the renewable energy sector.

3. Research methods

This article seeks to bring together results from research conducted as part of a wider project on renewable electrification in Kenya entitled Innovation and Renewable Electrification in Kenya (IREK), which examines the implementation of wind and solar technologies in Kenya's renewable electrification process [17]. This article distils insights from reports produced for the project which also include further detailed information on each of the sub-sectors [18,19] as well as on ongoing research work by the five authors.

The main source of information for Sections 4 and 5 of this article was semi-structured interviews with key actors involved in the sectoral systems. Information derives mainly from interviews carried out in Nairobi in 2016 and 2017. Actors and organisations interviewed include project developers, regulators, investors, plant operators, technology suppliers, donor agencies and government agencies. Interviews were conducted using predeveloped interview guides with predefined questions tailored to the specific interviewees in question. The data was analysed by operationalising the three main features of the SIS perspective described above to capture the innovation dynamics within the RE sector in Kenya. Data collected in interview were compiled into the three main categories of the SIS perspective across the four sub-sectors, using the tabular approach suggested by Miles and Huberman [20]. The subsequent analysis focused on condensing and distilling the main findings within each of the four sub-sectors

To gain an overview of the market status and trends and to triangulate information, desk research has reviewed and consulted a large variety of documents, including papers from the peer-reviewed literature, media reports, presentations, company press releases, and industry and other reports. Data collected from documentary sources used a similar approach by identifying events (e.g. project or policies) addressing the SIS dynamics across the four sub-sectors.

4. Solar PV and wind market status and trends in Kenya

The following sections will report on the status of market development in Kenya across the mini-grid and large-scale market segments for wind and solar PV technologies respectively, following the structure shown in Table 1. As seen the different technology domains made up of various shapes and sizes, relate wider pathway dimensions regarding the deployment trajectories evolving in either distributed mini-grids or grid-connected projects.

4.1. Wind-powered mini-grids

The wind-powered mini-grid market segment in Kenya includes a mixture of state-owned mini-grid power stations and commercially operated mini-grids. As the information available regarding these facilities is generally scarce, the following overview has been assembled from a variety of sources from the period 2013–2016.

According to these sources, there were 21 state-owned mini-grid stations in Kenya in 2016. The majority are owned by the Rural Electrification Authority (REA) and operated by the Kenya Power and Lighting Company (KPLC), while two are operated by the Kenya Electricity Generating Company (KenGen) [21]. The mini-grids include diesel-fired generators and combined hybrids with solar and wind. The two wind hybrid plants are operated by KPLC and include the diesel–wind hybrid plant in Marsabit (500 kW) and a solar–wind–diesel hybrid plant in Habaswein (50 kW), with a combined total installed wind-power capacity of 0.55 MW (Table 3) [22].

A number of companies also offer wind and solar-powered mini-grids to villages and households on a commercial basis. Anecdotal evidence of the scale of this market varies from at least a dozen wind/solar/micro-hydro/hybrid mini-grids to eighty to a hundred small wind turbines (400 W), often installed as part of a solar PV–wind hybrid system with battery storage [10,23]. These have been installed by telecoms players, NGOs and both commercial and household clients. Private companies operating in Kenya with expertise and activities in wind-powered mini-grids include PowerGen, Wind for Prosperity Kenya, CraftSkills, WinAfrique, Chloride Exide, and Davis and Shirtliff [24,25].

Table 1
Technology system sub-categories of wind and solar PV.

	Wind	Solar
Small	Wind-powered mini-grids (Section 4.1)	Solar-powered mini-grids (Section 4.3)
Large	Grid-connected wind-power plants (Section 4.2)	Grid-connected solar-power plants (Section 4.4)

There are references to the use of small-scale wind energy for water pumping in Kenya going back to the early twentieth century, and by 2005 about 300–450 wind-powered water pumps were estimated to be in operation [26]. With respect to electricity-producing wind turbines, one local Kenyan manufacturer has been active since the late 1990s, and three foreign manufacturers started activities in 2010–2011 by installing a small number of wind turbines. From around 2011, however, domestic wind turbine suppliers have increasingly shifted their focus and activities toward the emerging market for solar-powered mini-grids, as in the case of the companies RIWIK and SteamaCo. To explain this shift, AHK [24] referred to the limited size of the domestic market for wind turbines compared to the emerging market for solar PV (across market segments), while other interviewees mentioned the decrease in the price of solar panels and their relative ease of installation and maintenance compared to wind turbines. Kamp and Vanheule [26] estimate that around twenty companies currently offer imported wind turbines, but they are predominantly installers of solar PV systems that complement their energy product portfolio with wind turbines. Locally produced wind turbines are typically in the range of 150 W–3 kW, and between 120 and 150 wind turbines within this range have been installed in Kenya to date [27]. The typical size of commercial solar-powered mini-grid systems currently offered by domestic suppliers in Kenya is in the range of 15–100 kW. Given their lower capacity level, the locally produced wind turbines are smaller and not well-suited to catering to this market. Imported turbines are in the range of 1–5 kW, and their average efficiency, reliability and price are generally higher than those of locally produced wind turbines.[2] According to Kamp and Vanheule [26], an increasing number of local manufacturers are offering imported turbines from China, but detailed information about Chinese wind turbines installed in Kenya is thus far limited.

A number of new wind-powered mini-grids are being developed. AHK [24] listed five new wind–diesel hybrid mini-grids currently under construction in Kenya with a total capacity of 600 kW. The Kenyan government's rural electrification master plan from 2009 also included support for the retrofitting of existing diesel-based decentralised power stations into hybrid schemes with wind and solar PV [1]. As part of the implementation of the master plan, 44 new sites are planned for development as hybrid mini-grids, including nineteen wind turbines with a total capacity of 1.9 MW [24]. The development of mini-grids in Kenya is supported by various donor organisations, such as the World Bank's Scaling-up Renewable Energy Program (SREP), which aims to install 3 MW of wind and solar hybridized with the existing diesel generators in twelve isolated grids with a total installed capacity of

[2] The price of small-scale wind turbines (150 W–300 W) sold in Kenya is around KES 100.000–200.000, while the price range of turbines of around 1 kW are KES 280.000–350.000 and can reach up to KES 800.000 for larger turbines (of 3 kW) [56].

11 MW [22]. Similarly, the Department for International Development (DfID) and the German Corporation for International Cooperation (GIZ) provide various kinds of support for the hybridization of existing diesel-fired mini-grids with wind or solar PV and the development of private mini-grids. However, none of these organisations appear to have an explicit focus on wind-powered mini-grids, and they mainly concentrate on supporting the development of solar-powered mini-grids.[3] One notable exception is the UNIDO-funded project in the Ngong Hills implemented in 2009, which involves a solar–wind–diesel hybrid mini-grid with a total installed capacity of 10 kW (including a 3 kW wind turbine) [28].

4.2. Large-scale, grid-connected wind-power projects

At present there is only one operational, large-scale, grid-connected power project in Kenya: the 25.5 MW Ngong Power Station, which comprises six 850 kW Vestas turbines and 24 Gamesa 850 kW turbines. The plant is owned by KenGen and was established in 1993 with two turbines donated by the Belgian government. Four additional large-scale wind-power projects are currently under development in Kenya, including the prominent Lake Turkana project (310 MW), the Kipeto Energy Wind Park (100 MW), the Kinangop Wind Park (60 MW), which has recently been cancelled at a late stage in its project development, and the Baharini Electra Wind Farm project (90 MW).

The largest and most advanced project is the Lake Turkana Wind Power project, which has been developed by a consortium of international actors, including the Danish Investment Fund for Developing Countries, Vestas, the Finnish Fund for Industrial Cooperation and KLP Norfund Investments. The project is located in the area around Lake Turkana in northern Kenya and involves the installation of 365 (850 kW) Vestas turbines, which are imported from China [29]. It is often mentioned as the largest wind-power project in sub-Saharan Africa and will add what corresponds to approximately 15% of total installed electricity generating capacity in Kenya. Although the power purchasing agreement (PPA) had already been signed with KPLC in 2010, the construction of the wind turbine park was completed in early 2017. However, delays in the construction of the transmission line to connect the project to the national grid have led to uncertainty regarding the project's exact commissioning date.

A consortium consisting of the African Infrastructure Investment Fund, Craftskills Wind Energy International Ltd., the International Finance Corporation and the Kipeto Local Community Trust own the Kipeto Energy Wind Park. In 2015, the consortium signed a PPA with KPLC, and at the beginning of 2016 the Chinese company, China Machinery Engineering Corp., was contracted as the EPC contractor.[4] The project will include the installation of sixty turbines supplied by General Electric. According to the ERC [30], however, the PPA has not yet been agreed and is still undergoing evaluation.

The African Infrastructure Investment Fund II and Norfund originally provided the funding for the Kinangop Wind Park project with debt finance supplied by the Standard Bank of South Africa. The project was planned to have been completed in 2015, with 38 turbines supplied by General Electric and Iberdrola as the EPC contractor in cooperation with the Kenyan-based consultancy company Aeolus Kenya Ltd. The project experienced delays and was eventually cancelled in early 2016 [29]. A number of media reports have claimed that the cancellation of the project was mainly due to local opposition relating to land rights issues [31–33].

The Baharini Electra Wind Farm project is financed by the World Bank's International Finance Corporation and will be carried out by Belgian Electrawind in collaboration with local partner Kenwind [34]. It seems that the project has not advanced beyond the initial feasibility and planning stage. This means that financial closure and a PPA have not yet been agreed and that technology suppliers and contractors have not been identified.

The above projects are being developed in connection with the Kenyan feed-in tariff for wind-power projects, which was first introduced in 2008 and later revised in 2012. The current tariff offered for wind-power projects in the range 50–100 MW is US$ 0.11/kWh [35]. The feed-in tariff for wind-power projects has attracted interest from a number of private developers, donors and development banks, which have provided financial support and advisory services to move the project toward reaching financial closure [33]. This has resulted in a high number of applications submitted under the FIT. WinDForce [35] reports that by 2013 a total of 236 applications had been submitted under the FIT system, of which twenty had been approved. However, as none of these projects has signed a PPA or progressed to full operation, it appears that movement on the ground has been slow. The Lake Turkana project provides an illustrative example, reaching financial closure nine years after it had begun.

4.3. Solar-powered mini-grids

Eight state-owned solar-powered mini-grid stations are currently in operation in Kenya, including seven solar–diesel hybrids and the wind–solar–diesel hybrid mentioned previously (see Table 2). The total installed capacity of these solar-powered mini-grids, which are owned by REA and operated by KPLC, is 0.51 MW (see Tables 4 and 5 below) [36]. More detailed information on these state-owned, solar-powered mini-grids in Kenya is generally scarce. However, in general, European companies specialising in the supply of core solar technology components to mini-grids and related engineering and consultancy services are strongly represented in Kenya, especially companies from Germany. Examples of German-based companies supplying such components, which include panels/modules, inverters, controllers and batteries, include Energiebau Solarstromsysteme, Donauer Solartechnik and Juwi AG. These foreign companies are typically closely linked to local project developer companies in Kenya, such as Harmonic Systems Ltd., Dreampower (local subsidiary of an Italian company) and Solar Works Ltd. in the development of different projects.

The existing solar PV industry in Kenya includes one local assembly plant entitled Ubbink East Africa Ltd., which supplies solar PV panels

Table 2
Mini-grids owned and operated by KPLC in Kenya in 2015.
Source: [25].

Mini-grid	Type	Nominal capacity (kW)	Effective capacity (kW)	Customers
Baragoi	Diesel	248	138	230
Eldas	Diesel	184	184	80
Elwak	Hybrid Solar	740	610	802
Habaswein	Hybrid Solar and Wind	760	542	1015
Hola	Hybrid Solar	1220	660	1956
Lodwar	Hybrid Solar	2740	1480	2380
Lokichoggio	Diesel	680	500	166
Mandera	Hybrid Solar	2350	1480	4000
Marsabit	Hybrid Wind	2900	2800	3300
Merti	Hybrid Solar	250	170	436
Mfangano	Hybrid Solar	520	390	120
Mpeketoni	Diesel	1285	950	1503
Rhamu	Diesel	184	184	2132
Takaba	Hybrid Solar	244	244	300
Wajir	Diesel	3400	3130	4100
Total		**17,705**	**13,462**	**20,598**

[3] See, for example, the recent announcement by the French development agency to "*support the installation of RE generation units (primarily solar photovoltaic [PV], but also in some cases wind turbines) in 23 mini-grids currently powered by diesel generators*" [57].

[4] Engineering, procurement and construction (EPC) contracts are a prominent form of contractual agreement in the construction industry. The EPC contractor carries out the detailed engineering design for the project, procures all the equipment and materials necessary, and then undertakes the construction in order to deliver a functioning facility or asset to its clients.

Table 3
Key characteristics of the two existing wind-powered mini-grids in Kenya.
Source: authors' own elaboration.

	Marsabit	Habaswein
Installed wind capacity	Two 250 kW wind turbines	Three 20 kW wind turbines
Total system supplier	Socabelec East Africa Ltd.	
Turbine supplier	Vergnet Groupe (France)	Layer Electronics S.R.L (Italy)
Key component supplier	ABB PowerStore system (500 kW)	
Start date of operation	Scheduled for completion in 2016	

Table 4
Installed capacities of wind and solar in existing mini-grids in Kenya.
Source: [60,61].

No.	Station	County	Installed diesel capacity (kW)	Installed wind capacity (kW)	Installed solar PV capacity (kW)
1	Wajir	Wajir	1746	0	0
2	Mandera	Mandera	1600	0	300
3	Marsabit	Marsabit	560	500	0
4	Lodwar	Turkana	1440	0	60
5	Hola	Tana River	800	0	60
6	Merti	Isiolo	128	0	10
7	Habaswein	Wajir	360	50	30
8	Elwak	Mandera	360	0	50
9	Baragoi	Samburu	128	0	0
10	Mfangano	Homabay	584	0	0
Total			**7706**	**550**	**510**

Table 5
Key characteristics of the Mfangano solar-powered mini-grid.
Source: [45].

Installed solar capacity	40 kWp (no battery)
Total system supplier (EPC)	Dreampower and Juwi AG
Commissioning	2013
Core components	N/A

with capacities between 13 and 240 Wp (the bulk of sales are of 40 Wp modules) and a number of local battery producers/suppliers, such as Chloride Exide Ltd. [37,38]. However, it appears that the local industry is mainly focused on serving the Kenyan market for domestic solar systems and smaller scale solar applications for individual households [39]. It seems evident, therefore, that most of the core system components in the solar-powered mini-grids in Kenya are imported from abroad, typically from renowned European or American companies through local sales offices and wholesale retailers [24].

A further fifteen state-owned, solar-powered mini-grids are currently under construction in Kenya with a total capacity of 2 MW [24]. A further nine solar-powered mini-grids with a total capacity of 1.8 MW are being developed as hybrid solar–diesel mini-grids (in existing diesel-fired plants), and an additional 25 plants (with a total capacity of 5.6 MW) are at the initial proposal stage. Most recently, REA has announced a call for tenders for the development of 25 new solar-powered mini-grids [40]. Donor organisations also actively promote the development of solar-powered mini-grids in Kenya by providing financial support to specific projects, such as the development of up to 26 new solar-powered mini-grids (mainly solar–diesel hybrids) by the KfW Development Bank and GIZ through the German development agency [21]. Similarly, DfID and the World Bank have provided direct investments for the development of new (greenfield) solar-powered mini-grids, including the recently launched Kenya Off-grid Solar Access Project (KOSAP) [41], while the Spanish embassy has provided financing for the development of five new solar–wind–diesel hybrid mini-grids. Other donor-funded projects include the DfID-funded co-operative-based Kitonyoni mini-grid (a solar–diesel hybrid of 13.5 kWp), the UNIDO-funded, community-based Olosho Oibor mini-grid (a solar–wind–diesel hybrid of 10 kWp) and two solar-diesel hybrid mini-grids funded by GIZ: the Talek Power mini-grid (50 kWp) and the Strathmore University solar hybrid system (10 kWp) [10,28,42].

A number of private companies are involved in supplying solar-powered mini-grids on a commercial basis in Kenya, which include Powerhive East Africa Ltd., PowerGen and Talek[5] [25]. Since 2012, these foreign-owned companies have installed between twenty and thirty solar-powered mini-grids with a capacity of 1.4–10 kW with a few examples of larger systems (20 and 50 kW). Two of these companies have received a formal license to operate, and one has secured financing to establish a portfolio of another hundred mini-grids [10,43]. These companies have had initial pilot phases and are now in the process of significantly upscaling their activities in Kenya [44]. Most of the core components used in these solar-powered mini-grids are sourced from renowned suppliers from Europe or the US either in-house or through external suppliers. It should be noted that SteamaCo has developed a smart metering system, which has been installed in a number of solar-powered mini-grids in Kenya along with related software services.

4.4. Large-scale, grid-connected solar-power projects

Currently, there are five grid-connected solar power plants in operation in Kenya. These include: (i) a 575 kWp plant installed at the UN compound in Nairobi; (ii) a plant at the SOS Children's Village in Nairobi (60 kWp); (iii) a 100 kWp plant installed at Kenyatta University; (iv) a 72 kWp system installed at a flower farm; and (v) a 1 MWp plant at a tea-processing facility [24,39]. While the first three plants were financed mainly by international donors, the latter two were financed by the owners of the industrial plant. The existing plants appear to have been delivered on a turnkey basis by total system suppliers from abroad in cooperation with local consultancy companies and installation contractors [45]. For example, the German company Energiebau Solarstromsysteme GmbH was the turnkey provider of the first-mentioned plant in cooperation with the Kenyan-based company SolarWorks, which included the sourcing of all of the core components, mainly from European suppliers (modules from Schott Solar and Kaneka, and inverters from SMA Solar Systems) [24,46]. Similarly, the second plant was constructed by the UK-based company Arun Construction Services in cooperation with the local company Azimuth Power (modules from Centrosolar AG and inverters from SMA Solar Systems) [46]. In the fifth plant, the tea-farm owner commissioned the UK-based company SolarCentury to deliver the plant, including imports of key components, in cooperation with the Kenyan-based companies East African Solar Ltd. and Azimuth Power [47]. An additional plant at Strathmore University (0.6 MW), which signed a PPA in 2015 has recently been commissioned and is currently in operation. In this project, the Kenyan companies Questworks and ReSol have been contracted as the total system provider and installation contractor respectively, and key components will be sourced from European and Chinese suppliers (including panels from JinkoSolar and inverters from Solaredge). In general, the involvement of additional local companies in the above-mentioned plants seems to be limited mainly to local technicians and engineers during the construction stage, as well as local contractors of maintenance services during operation.

A number of projects on a significantly larger scale seem to be under

[5] The Talek power company has been created as a so-called 'special purpose vehicle' by the German development agency GIZ and has been set up as a private company in trust [9,37].

Table 6
Projects approved by the ERC to be developed under the feed-in tariff system (2015).
Source: [30].

Technology	No. of applications	Proposed capacity (MW)	Approved capacity (MW)	Percentage (%)
Wind	1	50.00	50.00	11.80
Hydro	0	0.00	0.00	0.00
Small Hydro	13	85.95	85.95	20.30
Geothermal	0	0.00	0.00	0.00
Solar	3	120.00	120.00	28.40
Biogas	6	167.30	167.30	39.50
Co-generation	0	0.00	0.00	0.00
Total	23	423.25	423.25	100.00

Note: the list only involves projects for which expressions of interest (EOI) have been approved by the FIT evaluation committee.[a]

[a] In the three previous annual reports prepared by the ERC, the number of solar projects listed as 'approved solar PV projects' were 20, 16 and 9 respectively, indicating that since 2012/13, 48 solar power projects have been approved under the FIT, none of which have been realized or have a signed PPA as yet.

development in Kenya as part of the feed-in tariff system, which currently offers a tariff of US$ 0.12/kWh for project developers [30] (see Table 6). This includes the Samburu project (40 MW), the Garissa project (50 MW), the Greenmillenia Energy project (40 MW), the Nakuru project (50 MW), the Kopere Solar Park project (17 MW), the Witu Solar Power project (40 MW) and the Alten Kenya Solarfarm project (40 MW) [39,48]. These projects are being developed by foreign technology suppliers and companies specialised in large EPC contracts in the energy sector, such as Stimaken and Martifier Solar. Common to these planned projects is that none of them appears to have advanced from the stages of initial expressions of interest and feasibility studies to reach financial closure and the signing of PPAs. It appears that the various project developers are generally struggling to secure funding and reach financial closure [33,45]. Hence, as project planning and preparation for most of these projects had started already in 2012, movement on the ground seems relatively slow, and most of these projects have not yet reached the construction or operational stages [30,33]. A number of donors and development banks, such as the World Bank and the German development agency, support most of these projects.

4.5. Summary of solar and wind market trends and status

Looking at the overall wind sector, there is clear variation in the dynamics of small- and large-scale wind. The market for small-scale wind-based mini-grids appears to have stalled: very few hybrids exist or are planned, and private suppliers of wind-powered mini-grids have shifted focus. In contrast, the market for large-scale wind projects is moving forward, with the flagship Lake Turkana project drawing massive attention, together with a number of other large-scale projects.

In the overall solar sector, the market for small-scale solar-based mini-grids is currently experiencing a period of significant momentum, with both private mini-grid operators and many donors involved with existing and planned hybrid greenfield mini-grids [49]. On the other hand, the market for large-scale solar projects has only moved to a very limited extent on the ground, as existing projects are small in scale, and large-scale projects remain at the planning stage. In the next section, these trends will be compared to the characteristics of the four disaggregated SISs.

5. The size and shape of wind and solar sectoral innovation systems

In the following sections, the characteristics of the four SISs are explored and disentangled. The SIS perspective is used to describe the three dimensions – knowledge base, actors and institutions – of the wind and solar sectors across the size and shape of the projects. Based on the market trends presented above, the following descriptions of the system characteristics aid the discussion of the potential differences in the relative strength of the four SISs in respect of generating and diffusing solar PV and wind technologies in Kenya.

5.1. Sectoral innovation system characteristics of wind-powered mini-grids

The existing knowledge and technological base in the domestic industry for wind turbines in Kenya is characterised by relatively simple and small-scale technologies manufactured locally. Such small-scale systems can be tailored to different local contexts and manufactured from a range of locally available materials while still being relatively robust. As the turbines are typically produced by smaller manufacturers, universities or NGOs involved in community projects, they do not require advanced engineering knowledge or skills. Thus, as opposed to formalized R&D, the domestic industry for small-scale wind turbines is generally characterised by a high level of informal knowledge and learning in the way that local artisans and blacksmiths tinker with various designs based on the available equipment and materials. While the wind turbines are produced and diffused at relatively low cost, final performance and standards tend to vary greatly. The locally produced systems are contrasted with the imported turbines used in the existing wind–diesel hybrid mini-grids, which are generally higher in performance and price levels [27]. Due to the lack of experimentation with wind-powered mini-grids, related technical concepts and commercial applications, limited specialisation and experience has been accumulated in this area. The main supportive institutional conditions promoting the development of wind-powered mini-grids are related to initiatives adopted as part of the rural electrification master plan to hybridize the existing diesel-fired mini-grids with wind and solar [1]. These initiatives are supported and complemented by various donor programs but are also driven by the increasing operational costs of the existing diesel-fired mini-grids. The main actors involved in the domestic industry are local wind turbine manufacturers, NGOs and local community entrepreneurs involved in various small-scale projects typically implemented by donors in rural villages [50,51]. A number of these projects include individual engineers and NGOs from abroad involved in testing a specific technical design for rural applications [52]. The local manufacturers rely on local supply chains and distribution networks and typically make use of connections in the local environment for sourcing materials and related know-how. Government agencies promoting rural electrification in off-grid areas are typically also involved in specific projects either directly or indirectly via technical support. The Ministry of Energy and Petroleum is also involved in the installation of wind speed data loggers at 20 m and 40 m. Local universities sometimes provide highly applied research input to specific projects such as a collaboration between Jomo Kenyatta University of Agriculture and Technology and the Japanese Government on small wind technology, but formalized R&D activities at universities focusing specifically on small scale wind is largely absent in Kenya.

5.2. Sectoral innovation system characteristics of large-scale, grid-connected wind power projects

The knowledge and technology base underlying the development of advanced large-scale wind turbines has evolved into a highly researched and capital-intensive process involving the continuous development of new materials, designs and production methods. Thus, the development of utility-scale wind turbines involves both internal R&D carried out within industry lead firms and formalized R&D undertaken by research centers at universities or public research organisations. These R&D activities mainly draw on technical disciplines and engineering-based knowledge. The ongoing development efforts focus on improving the price and performance of wind turbines in order to increase the competitiveness of wind power compared to conventional sources of energy for power generation. As economic feasibility generally increases with the size of the wind turbines, the general trend in the industry has been towards the gradually increasing scale of wind turbines. The development of large-scale wind-power projects also draws on a broader set of organizational and administrative competences, including the skills and systems for turbine component manufacturing (e.g. supply chain management) and the knowledge required for EPC contracting and the incorporation of third-party consultants (legal advice and engineering consultancy). In the projects under development in Kenya, the main contractors and wind-turbine suppliers have drawn upon a range of such knowledge bases and areas of expertise during project development. International actors, such as pension funds, development banks, donors and other types of financial institutions, play an important role in providing finance for the development of the projects. Due to the high national relevance of the projects as large infrastructure investments, national policy-makers, regulatory bodies and government agencies are also involved in developing them. The government support for large-scale wind (and solar) is part of a broader objective to attract foreign investment in Kenya by making possible the inclusion of private, independent power producers (IPPs) in the energy sector. While direct involvement includes bilateral negotiations between project developers and the relevant authorities, indirect involvement includes political advocacy influencing the projects. While not being directly involved, local community and actor groups exert a strong indirect influence on project development, mainly due to disagreements over land rights issues. The main supporting instrument promoting the development of large-scale wind-power plants in Kenya is the feed-in tariff, which applies to projects with a capacity over 50 MW.

5.3. Sectoral innovation system characteristics of solar-powered mini-grids

The knowledge base underlying the development of solar-powered mini-grids in Kenya draws on a variety of disciplines and relies particularly on foreign expertise. In the case of the state-owned solar–diesel hybrids, the main expertise needed is in the area of turnkey contracting. The necessary technological skills of the total system suppliers relate mainly to the capacity to design the plants, manage the sourcing of key components and undertake the construction and final commissioning of the plants. Since this expertise is not currently available from domestic suppliers in Kenya, European companies with significant experience in turnkey contracting and related engineering tasks dominate the development of these plants. Despite the technical capacity and knowledge accumulated in the domestic industry for solar home systems [37], the local suppliers of core components (such as panels and batteries) seem disconnected from the development of solar-powered mini-grids. The private companies from abroad supplying solar-powered mini-grids on a commercial basis in Kenya draw mainly on engineering-based knowledge in the ongoing technical experimentation efforts to optimize their mini-grid systems. Experience from the telecommunications industry has also provided input into the development of a business models based on pay-as-you-go (PAYG) systems specifically developed to target poor customers in rural, off-grid areas. This business model draws on knowledge about IT and software solutions and related data analysis and optimization systems, as well as the use of smart metering and monitoring technologies. Some of these companies are engaged in client relations with (private) investors in solar-powered mini-grids, some of which are philanthropic foreign investors [43]. Collaborative networks have been established across a number of these companies, as well as linkages to foreign investors, headquarters and component suppliers in Europe and the US. A number of state and donor-funded programs to hybridize the existing diesel-fired mini-grids are greatly influencing the enabling environment for the development of solar-powered mini-grids in Kenya. However, the existing regulatory framework for rural electrification, which focuses on conventional grid-extension programs, continues to play an important role in the development of commercial solar-powered mini-grids, resulting in lengthy approval and negotiating processes for project developers.[6] Challenges faced by many solar mini-grid developers still often include access to finance or ensuring affordability of the projects as the higher cost of such small-scale energy production is borne by the consumers. The lack of focus on such new models for producing and distributing energy is also visible in the policy frameworks, where grid-owners and operators have called for stronger and clearer regulation regarding tariffs, integration, standards, licensing as well as the possibility for subsidy schemes [49].

5.4. Sectoral innovation system characteristics of large-scale, grid-connected solar power projects

A key driver for the development of large-scale solar power plants in Kenya is the rapidly decreasing costs of solar panels. The experience of plants under development in Kenya indicates that designs for large-scale solar power plants are generally well proven globally, requiring only minor design and construction modifications to adapt them to local conditions. The knowledge and technological base underlying the development of large-scale solar power plants in Kenya thus draws greatly on foreign expertise in the delivery of plants on a turnkey basis. European companies with substantial experience in turnkey plant engineering, component sourcing and commissioning have thus delivered the existing plants in cooperation with locally based consultancy companies. Due to the larger scale of the solar power plants currently under development in Kenya, their development draws on additional knowledge of EPC contracting and the related organizational expertise to manage the development of large infrastructure projects. Consequently, international contractors and technology suppliers with the technical expertise and management skills to develop an integrated plant design and to install and operate the system effectively have been involved in planning and developing the projects, as well as providing additional competences in the area of PPA contract negotiations, the legal aspects and detailed engineering tasks. While development of the existing solar power plants has included industrial users and donors as the project owners, the larger scale solar-power plants under development incorporate direct involvement from international investors, including development banks and donor organisations. However, the development of large-scale solar is generally being prevented by the difficulties project developers face in attracting finance from foreign investors, and concerns have been raised that the feed-in tariff system may be too low to incentivise foreign investments significantly [39].

6. Discussion: sub-sectoral dynamics across size and shape

Distinguishing sectoral innovation system features across market segments and technologies has shown that it is worth considering the similarities and differences between the size and shape of the different sub-sectors of solar PV and wind energy in Kenya. In the following sections the three dimensions of Malerba's [6] SIS framework are examined across the four sub-sectors (see also Table 7).

6.1. Differences and similarities between knowledge bases

Regarding the knowledge dimension, it is clear that both within and across the four SISs, each system is characterised by individually distinct knowledge bases. In fact, as noted by Malerba [6], it is knowledge and technology that place the issue of sectoral boundaries at the center of analysis. These differences therefore support the argument that a

[6] An example of the continued focus of the grid operator and energy planning agencies in Kenya on grid extensions to promote enhanced access to electricity for the rural population is the so-called 'Last Mile Connectivity Project' [59].

Table 7
Summary of sectoral innovation system dimensions across sectors.

Summary of system dimensions across sectors: Knowledge and technologies	
Wind mini-grids	• Small-scale and simple wind turbines • Informal learning and knowledge • Local craftsmen and engineers • Limited knowledge of wind-powered mini-grids • Absence of formalized R&D activities carried out at universities in small-scale wind turbines • Import of higher standard wind turbines
Large-scale wind	• Formalized R&D in large-scale wind turbines • Technical and engineering-based disciplines • Complex and capital-intensive capital goods • Experience in EPC contracting and planning of large-scale plants • Expertise in PPA contract negotiation and legal aspects • Design of project tailored to local conditions
Solar mini-grids	• Engineering-based knowledge • Telecom expertise (mobile payment schemes, PAYG models) • Smart metering and monitoring systems • Data management and software optimization tools Consultancy and donor experience
Large-scale solar	• Engineering-based knowledge • Experience in turnkey contracting • Experience in EPC contracting and planning of large-scale plants • Knowledge system design integration and operation
Summary of system dimensions across sectors: Actors and networks	
Wind mini-grids	• Donors, NGOs, local manufacturers involved in small-scale development projects • Actors embedded in local and regional supply chains and distribution networks • Universities involved in practical and hands-on applied research in specific projects • Absence of private suppliers of wind-powered mini-grids • Importers of foreign wind turbines
Large-scale wind	• Industry lead firms, such as Vestas and General Electric • International investors, including development banks, donors and pension funds • National policy-makers and key government agencies (e.g. via direct negotiation with project developers) • Local community groups (opposing projects)
Solar mini-grids	• European turnkey contractors • Local engineering and consultancy firms • Private suppliers of mini-grids owned by foreign expatriates • Foreign investors (direct plant investments and equity investments) • Foreign component suppliers Examples of cooperatives and community-based solar mini-grids
Large-scale solar	• International EPC contractors • Technology suppliers • International investors, including development banks and donors • Industrial users
Summary of system dimensions across sectors: Institutions	
Wind mini-grids	• State and donor support for hybridization of existing diesel-fired mini-grids • Apparent under-prioritization compared to solar mini-grids
Large-scale wind	• Feed-in tariff for wind-power projects • Financial and advisory support from donors and development banks
Solar mini-grids	• State and donor support for hybridization of existing diesel-fired mini-grids • Significant funding from foreign investors
Large-scale solar	• Feed-in tariff for wind-power projects • Financial support from donors and development banks

disaggregated sectoral analysis is necessary, perhaps particularly in respect of SIS size [8]. This is evident in that both large-scale wind and large-scale solar share some characteristics related to the size of the project, where EPC contractors and turnkey suppliers are present across the technologies. Many of the enabling aspects of this dimension are found in the intersections with the global sectoral characteristics where international actors have established themselves in the Kenyan market. This is notable because domestic actors seem disconnected, despite the technical capacity and knowledge that has been accumulated particularly in the domestic industry for solar home systems. There is little information on the involvement of local suppliers of either solar or wind components in any project. It is noteworthy, however, that across the solar and wind mini-grid sectors the knowledge base dimensions differ in terms of which actors with which knowledge bases are involved. While informal learning and knowledge characterize the wind mini-grid sector, the solar-mini grid sector features rather engineering-based knowledge, with more involvement from both private actors and international donors. The solar-powered mini-grid sector is also highly specialised, with business models and software catering to specific PAYG customer segments.

6.2. Differences and similarities between actors

In the actor dimension, foreign industry actors play a role across large-scale wind and solar mini-grids and large-scale solar. However, in wind mini-grids there is no significant presence of foreign industry actors; rather, small-scale domestic industry actors and foreign actors such as NGOs and donors focusing on small-scale development projects are dominant. While there are universities involved in practical and hands-on applied research in scientific projects, this does not translate into organized R&D in the domestic industry, and there is a notable absence of private suppliers of wind-powered mini-grids in the sector. In the solar mini-grid sector there are a number of private suppliers, foreign investors and foreign component suppliers, as well as turnkey contractors. Across both large-scale wind and solar power projects, the role of lead firms in the global industry in the wind sector and international EPC contractors is clear.

The role of local community actors is visible in both large-scale wind projects and solar mini-grids, though there is not much evidence of community involvement in wind mini-grid projects, and in the case of large-scale solar, the users tend to be large industrial players. In large-scale wind projects, the role of national policy-makers and governmental agencies has been notable through their direct negotiations with project developers over power purchasing agreements.

6.3. Differences and similarities between institutions

In terms of the institutional dimension of the SISs examined here, there are clear similarities in terms of the role of feed-in-tariffs and power purchasing agreements in the large-scale solar and wind projects, while small-scale projects in both the wind and solar sectors are influenced most clearly by state and donor support for hybridization of the existing diesel-fired mini-grids. What is noticeable, however, is that, despite the same overarching driver existing for the hybridization of mini-grids because of the increasing operational costs of diesel-driven mini-grids, the solar mini-grid segment differs markedly in terms of actors and networks and has received more attention from international donors than wind mini-grids. A number of donor programs and national plans also mainly support the development of hybrid wind-diesel mini-grids. However, compared to the support for solar-powered mini-grids, the development of wind-powered mini-grids seems to be somewhat under-prioritised in these initiatives. In a number of locations, especially in the eastern and northern parts of Kenya (such as the area surrounding Lake Turkana), which have particularly favorable wind resources, the development of wind-powered mini-grids can become economically viable, although optimizing location also depends on local demand [53].

Overall, the solar mini-grid market appears to have a more enabling environment that has led to the establishment of a commercial market for the sale of electricity services to rural communities. This private-sector approach to the provision of rural electrification via mini-grids seems to be unprecedented in Kenya and East Africa. Many of the active companies have been started by foreign expatriates with significant expertise in business start-ups, engineering, RE consultancy, telecommunications and donor organisations. These companies have therefore brought a high level of technical and organizational expertise and management systems into Kenya, which has been combined with knowledge on energy use and needs in local communities collected by the companies over time [54]. However, across both wind- and solar-powered mini-grids, the challenge remains of the lack of a regulatory framework for the development of commercial mini-grids. Bilateral negotiations between the companies and key government agencies related to obtaining operational licenses and approvals of end-user tariffs have shown to be challenging and lengthy [21]. The prolonged negotiating process is partly related to the different objectives of government agencies and private operators. The commercial tariff proposed by the private companies is significantly higher than the universal tariff offered by the government through the conventional grid-extension programs to support rural electrification. The regulatory authorities are generally hesitant in accepting the inclusion of private operators that are operating with business models based on low connection fees and high usage rates. In general, one aspect of the difficulties in attracting funding for RE projects is the unclear policy signals and ongoing discussions concerning the possible introduction of new incentive structures and regulatory models. Since the feed-in tariff system was revised in 2012 to its current form, a number of alternative models, such as an auction system, competitive bidding and a net metering system for smaller grid-connected projects, have been discussed.

7. Concluding remarks: benefits and drawbacks of the SIS perspective

In this paper, we have aimed to analyse and understand innovation dynamics within and between various sub-sectors. Based on the SIS perspective adopted in this paper, there are not only profound differences between solar and wind technologies, but equally importantly also within these technologies. Overall, the SIS perspective shows that, in terms of the key system dimensions, there is a greater similarity between large-scale wind and solar projects (size), rather than between projects within the same technologies (shape). The large-scale projects are characterised by scientific knowledge bases (R&D), with actors with EPC experience or turnkey contracting playing a large role. The projects are capital–intensive, involve management expertise and PPA negotiations, and generally involve foreign actors in terms of both technology and expertise, as well as investments. The large-scale sectors differ from small-scale wind and solar mini-grids, which are markedly characterised by decentralised electrification efforts and are highly dependent on tariff structures and cross-subsidies. The rural electrification domain is connected to discussions about grid extensions and sees many donor-driven hybridisation efforts (particularly in solar). However, it has also revealed that there are significant differences between the institutional conditions such as regulation and policy frameworks for wind and solar mini-grids, with the solar mini-grid SIS being strengthened by a range of drivers that have led to an unprecedented private sector-driven approach. In contrast, the wind-power mini-grid projects seem to have suffered both from the comparative success of the solar mini-grid market and the apparent under-prioritisation of the sector by actors otherwise engaged in the mini-grid sector.

By making such comparisons and contrasts, the SIS perspective has allowed us to explore some of the drivers and barriers of the four sub-sectors. For example, across the institutional dimension it becomes clear that the drivers or institutional incentives share more similarities in size than in shape. However, these institutional incentives do not reflect the differences across actors and knowledge bases. For example, although the institutional incentives are largely similar across the small-scale solar PV and wind sectors, the large differences in knowledge bases and actors have led to the two sectors evolving at different tempos. There is an apparent lack of actors and networks driving small-scale wind, while highly specialised foreign-owned companies have contributed to the small-scale solar sector, which has experienced significant momentum in recent years. Similarly, the knowledge bases differ markedly and connect to global trends within each of the two technologies, where globally the wind industry is focusing more on developing larger and more efficient turbines rather than small-scale turbines, while the solar industry has connected to business models that focus on smaller scale applications (e.g. PAYG models).

Using the SIS perspective has thus served the purpose of teasing out differences that may otherwise have gone unnoticed using a more aggregated sectoral approach to the emerging RE sector. While the broader definition of sectors, such as RE, or even solar PV or wind as broad sectors has been used to emphasise interdependencies, linkages and transformations, in some cases the disaggregated level highlights rather the coexistence of different innovation systems within broadly defined sectors. Within the context of rapidly emerging energy systems, we argue that the disaggregated level of analysis is particularly important in designing policy, as a broad RE policy approach should consider nuances of SIS across size and shape, particularly in countries where the process of electrification is ongoing. Such a perspective is aligned with the suggestion by Malerba that "*the appropriate level of analysis in terms of agents, functions, products and agents depends on the specific research goal*" [9]. However, a disaggregated level of analysis could be of use more broadly in research in other sectors beyond RE using the SIS perspective in order to capture in detail the innovation dynamics within specific sectors. Whereas the SIS perspective was initially developed to cater for research conducted at different levels of aggregation, most empirical studies adopt a highly aggregated focus. We therefore suggest taking the initial suggestion by Malerba [6] to conduct research on SISs at different levels of aggregation more seriously.

We posit that such an approach is highly relevant for the analysis of pathways − or 'directions of development' in the energy field. Such energy pathways of course rely on the specific core technology choices that determines its 'shape' in terms of a given energy mix, involving different renewable energy technologies. But we argue that equally, or even more, important is the issue of 'size' because of the ramifications of this choice for the sustainability and inclusiveness of the pathways. This choice may be particularly relevant for the prospects of producing technologies locally, using local services for constructing facilities, and involving local labour in operation and maintenance. The size choice is at the core as a defining element of alternative renewable electrification paradigms, regardless of whether such electrification is achieved by harnessing the sun, wind or water flows. While the paper has focused on wind energy and solar PV, further research needs to address whether similar conclusions may be reached when it comes to other renewables that may also be deployed in either large scale (more centralised) or small-scale (more decentralised ways), such as hydro-power.

Our conclusions have important implications for ongoing policy discussions on shaping electrification pathways. It supports the opposition to any 'one size fits all' policy incentive in the renewable energy sector − rather, policy-makers should think about how they want to shape electrification pathways across the sizes and shapes outlined here. Tailor-made policies can help shape the dynamics of each sub-sector, and stakeholders and decision-makers should ask themselves which aspects should be enhanced? The SIS perspective highlights how innovation systems are outcomes of interaction and co-evolution of both size and shape, but also across national borders and links to global industry trends. Yet the literature has also pointed out that knowledge created in specific sectors may not be easily acquired and transferred across sectors. Therefore, attention to nurturing each of these distinct sectors, how to set appropriate tariffs and incentives, but also how to establish a broader framework of technical and procedural regulations is required. The variations across sectors and the role of foreign expertise in driving certain sub-sectors also raises questions about building up the necessary capabilities and expertise within the local market. This call for future research to investigate further the 'structure' of sectoral systems and the kinds of policy mechanisms that may influence this. Furthermore, research into how interactions between and the co-evolution of such sub-sectoral innovation systems can help policy-makers understand how regulations and incentive mechanisms may influence co-existing and complementary sub-sectoral systems.

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